2017

The Effect of Delayed Onset Muscle Soreness on Jumping Mechanics and Performance

Ryan J. Engels
South Dakota State University

THE EFFECT OF DELAYED ONSET MUSCLE SORENESS ON JUMPING MECHANICS AND PERFORMANCE

BY

RYAN J. ENGELS

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Nutrition & Exercise Science

Specialization in Exercise Science

South Dakota State University

2017

THE EFFECT OF DELAYED ONSET MUSCLE SORENESS ON JUMPING MECHANICS AND PERFORMANCE

RYAN J. ENGELS

This thesis is approved as a creditable and independent investigation by a candidate for the Master Science in Nutrition & Exercise Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

Brad Bowser, Ph.D. Date
Thesis Advisor

Matthew Vukovich, Ph.D. Date
Head, Department of Health & Nutritional Sciences

Dean, Graduate School Date

ACKNOWLEDGMENTS

- To Dr. Bowser: I would like to thank Dr. Brad Bowser for the countless hours spent helping me throughout the many stages of this project. If it was not for your patience and ability to continuously push me none of this would have been possible. Thanks again so much for helping me along this journey and I know that if I ever need anything in the future you would be there to help.

- To Dr. Vukovich and September Kirby: I do not think words could begin to describe how much thanks I owe the both of you. Without your selflessness and willingness to donate what little time you have throughout the year, I would be lost. Thank you for constantly bringing a smile to all the participant's faces when they probably needed it!

- To Northland American College of Sports Medicine: Thank you for funding this project through the 2016 Innovative Student Research Grant. Without your generosity none of this would have been possible.

TABLE OF CONTENTS

Literature Review Tables

This literature review looks to capture the findings on the topics of delayed onset muscle soreness and biomechanics as it relates to the proposed study. For our literature review we have selected to use review tables. These tables are split into four main sub-categories that help break down the research specific to this topic. Throughout these review tables, the reader will obtain a better understanding of delayed onset muscle soreness, vertical jump performance and biomechanics, methodological considerations as it relates to the movement mechanics of the vertical jump, and strength training practices as it relates to injury prevention. These literature review tables intend to critically analyze the published information with regards to the proposed topic.

Table 1. Review of research on delayed onset muscle soreness with regards to injury protocol and performance changes

Author(s)	Year	Study Design	n	Exercise Intervention	Injury Location	Main Outcomes	PEDro Scale
Kanda et al. [9]	2013	Cohort Study	N=9 unhealthy males	Participants performed 10x40 repetitions.	Gastrocnemius and Soleus	Muscle soreness was highest 48-72 hours after testing. A positive correlation was demonstrated between the increase in neutrophil migratory activity at 4 hours and the increase in Mb concentration at 48 hours. The results show that neutrophils may be a possibly involved in muscle damage and inflammatory process.	6
Vila-Chã et al.[4]	2012	Cohort Study	N=10 healthy subjects	Subjects performed 4x25 maximum voluntary eccentric contractions.	Knee extensors	The present study showed that all examined force output profiles (maximal voluntary contraction, rate of force development, and force steadiness of the knee extensors) were disturbed. These alterations were accompanied by different adjustments of agonist and antagonist muscle activities. These compensatory mechanisms may increase the risk of further injury if a premature return to sport or exercise is attempted.	5
Kauranen et al. [10]	2001	Randomized Controlled Study	N=30 (12 males & 18 females) Divided subjects into two groups	Circuit Upper Body Training 10 different exercises for 3x30s	Upper Extremities	Mean CK values were significantly different post training.	6
Cheung et al.[2]	2003	Systematic Review	Age, sex, and fitness were not excluding factors Must have used	This is a review article that looks at different areas dealing with DOMS.	N/A	DOMS is found to significantly reduce joint ranges of motion. Peak torque deficits are most pronounced 24-48 hours post	N/A

			normal healthy participants			DOMS-inducing exercise. A reduction in force output by an injured part of a muscle may lead to compensatory recruitment which can cause unfamiliar stress and increased injury.	
Hedayatpour et al.[11]	2010	Cohort Study	N=10 healthy subjects	4x25 max voluntary concentric/eccentric contractions	Knee extensors	DOMS abolished the supranormal increase in EMG mean power spectral frequency following recovery from fatigue.	4
Tsatalas et al.[12]	2011	Cohort Study	N=19 females	5x15 maximal eccentric contractions	Knee Flexor and Extensors	Strength decrement was significantly different between knee extensors and flexors only 24 hours after eccentric exercise. Muscle-damaging exercise resulted in significant development of muscle soreness, decreases in isometric average peak torque and increases in CK activity at all time-points examined post-exercise.	7
Chen et al. [13]	2011	Cohort Study	N=17 sedentary males	5x6 maximal isokinetic (90° s−1) eccentric contractions of Elbow Flexors, Elbow Extensors, Knee Flexors, and Knee Extensors.	Elbow Flexors/ Elbow Extensors/ Knee Flexors/ Knee Extensors	Knee flexors are more susceptible to muscle damage than knee extensors. The difference in the susceptibility to muscle damage seems to be associated with the use of muscles in daily activities.	6
Armstrong [1]	1984	Systematic Review	This is a review article that looks at different areas dealing with DOMS.	N/A	N/A	Training is the only thing we are aware of that can prevent DOMS. Performance may be reduced during the period of DOMS both through reluctance to use the muscle because of pain, and	N/A

						through loss of inherent force-producing capability of the muscle.	
Cleak et al. [14]	1992	Cohort Study	N=26 female subjects	1x70 maximum voluntary eccentric contractions.	Elbow Flexors	A reduction in strength occurred, with maximal strength loss at 24 hours post exercise. Isometric strength remained 20% lower by day 11. If muscle damage and strength loss are a result of the program, unwanted stresses in the knee joint may be consequent upon a temporary loss of protective muscle function.	6
Behrens et al. [3]	2012	Cohort Study	N=15 healthy subjects (8 males & 7 females)	4x25 maximal voluntary concentric-eccentric contractions.	Knee Extensors/ Knee Flexors	Contractile proteins were impaired immediately after exercise at 24 hours after. Sensation of muscle soreness assessment revealed impairments at 24, 48 and 72 hours.	7
Clarkson et al. [15]	1992	Cohort Study	N=109 subjects	2x35 maximal eccentric contractions.	Forearm Flexor Muscles	Peak soreness is experienced 2-3 days post-exercise while peak swelling occurs 5 days post-exercise. CK levels increase 2 days after exercise which is also the time when spontaneous muscle shortening is most pronounced.	4

Table 2: Review of research on vertical jump biomechanics and performance

Author(s)	Year	Study Design	n	Outcome Variables	Main Outcomes	PEDro Scale
Schmitz et al. [16]	2014	Controlled laboratory study	N= 59 (30 males & 29 females)	Hip flexion motion & energy absorption Initial hip flexion & hip loading Knee loading Ankle loading & knee shear	A 90 minute IEP did affect VJ performance. A better understanding of lower-extremity biomechanics during explosive actions in response to IEP allows us to further develop and individualize performance training programs.	5
Wilson et al. [17]	2008	Controlled laboratory study	N=40 (20 with patellofemoral pain & 20 without)	Lateral Trunk Flexion Hip External Rotation Strength Hip Abduction	Women with patellofemoral pain demonstrated LE mechanics that differed from the healthy control group during single-legged jumping, particularly at the hip. Conservative treatment programs that include kinematic retraining as well as hip and trunk strengthening may improve patient outcomes.	6
Liederbach et al. [18]	2014	Controlled Laboratory Study	40 elite dancers (20 males & 20 females) 40 team sport athletes (20 males & 20 females)	Peak Knee Valgus Peak Hip Adduction Hip External Rotation Angle Peak Hip Internal Rotation Moment	Female athletes consistently exhibited landing patterns associated with a risk for ACL injuries when compared with the other 3 groups. Fatigue changed landing mechanics similarly in both dancers and athletes, such that all groups landed with worse alignment after being fatigued.	6
Kernozek et al. [19]	2008	Controlled Laboratory Study	N=30 athletes (14 females & 16 males)	Peak VGRF Anterior Hip Shear Force Peak Compression Force	Neuromuscular fatigue caused significant alterations in women that may be indicative of the	5

				Joint Moments	noncontact ACL injury mechanisms. Both men and women experienced lower knee extension moments and abduction moments. Current noncontact ACL prevention programs should incorporate a fatigue component to help minimize the deleterious effects of neuromuscular fatigue on landing mechanics.	
Wesley et al. [20]	2015	Cross-sectional Study	N=36 healthy college athletes (18 males & 18 females)	VJ Height Heart Rate LESS Scores	As evidenced by their higher LESS scores, females demonstrated more errors in landing technique than males, which may contribute to their increased rate of ACL injury. Both sexes displayed poor technique after the exercise protocol, which may indicate that participants experience a higher risk of ACL injury in the presence of fatigue.	8
Ortiz et al. [21]	2010	Cohort Study	N=15 recreationally active females	Peak Knee Landing Flexion Valgus Joint Angles Varus/Valgus Internal Moments EMG of quads/hamstrings	Greater knee injury–predisposing factors during the fatigued condition were observed but solely during the up-down hop task. Metabolic fatigue has been identified as one of the possible contributing factors to impair dynamic control and lower-extremity injuries. Strength and conditioning specialists need to be aware of how athletic performance can be affected by fatigue and associated mechanisms leading to increased risk for injuries.	7

Chappell et al. [7]	2002	Cohort Study	N=20 recreational athletes (10 males & 10 females) 19-25 years old	Peak Proximal Tibia Anterior Shear Force Knee Flexion-Extension Moment Knee Varus-Valgus Moment	The landing phase was more stressful for the ACL of both women and men than the takeoff phase in all stop-jump tasks. Results indicate that female recreational athletes may have altered motor control strategies that result in knee positions in which ACL injuries may occur.	4
Byrne et al. [22]	2010	Cohort Study	N=22 males	Reactive Strength CMJ Height	Two methods were used to determine optimal drop height. They are the maximum jump height method and the reactive strength index method. The study concluded that either method can be used to identify the optimal drop height in bounce depth jump training to increase CMJ performance, but the maximum jump height method should be used to improve reactive strength.	5
Brazier et al. [23]	2014	Systematic Review	N/A	N/A	Extreme levels of LE stiffness have been related to reduce joint motion and increased shock and peak forces in the LE. If a strength and conditioning coach is able to advance their athletes' ability to act like a "stiff spring" across an array of sporting movement patterns, performance enhancement may occur.	N/A

Table 3: Review of research with methodological considerations for the proposed topic

Author(s)	Year	Study Design	n	Outcome Variables	Main Outcomes	PEDro Scale
Byrnes et al. [24]	1985	Cohort Study	3 groups of subjects Groups bouts of exercise were separated by 3, 6, and 9 weeks	Plasma CK Levels Perceived Muscle Soreness Heart Rate	Used two 30 minute bouts of downhill running at a (-10 deg. slope) Maximal soreness was found at 42 hours post exercise It was concluded that performance of a single exercise bout had a prophylactic effect on the generation of muscle soreness and serum protein responses that lasts up to 6 week.	6
Schwane et al.[25]	1982	Cohort Study	N=7 healthy males	Plasma CK levels Plasma LDH levels VO_2 Stride frequency	Following downhill running CK was significantly elevated 24 and 48 hours later. There was no significant correlation between soreness rating and LDH levels. They could not definitively say that the soreness and CK increase was from the eccentric component of the exercise alone.	6
Jamurtas et al. [26]	2000	Randomized Control Study	N=24 untrained males Randomly assigned to one of 3 groups	Plasma CK Levels VAS soreness	CK concentration increased after exercise, peaked at 24 hours post exercise, and stayed elevated for 72 hours after the performance. The results from this study indicate that a novel exercise session with plyometric exercises can reduce the perception of muscle soreness and CK plasma levels.	4
Twist et al. [27]	2005	Cohort Study	N=10 male university level athletes	Plasma CK levels Knee Extensor Peak Power Output	On landing, participants were instructed to adopt a knee joint angle of approximately 90° in order to	5

					promote muscle damage; this protocol has been used successfully to induce muscle damage in the knee extensor group of muscles in previous studies. Peak power output and average sprint times were significantly different from their pretest values following the DOMS protocol.	
Braun et al. [6]	2003	Cohort Study	N= 9 trained distance runners and triathletes	VO_2 Heart Rate Lactate RER Ventilation	The key finding of the present investigation is that running economy was found to be compromised during the time course of DOMS. The potential ramifications of performing run training or participating in competition while experiencing DOMS would primarily be related to an increase in time to cover a fixed distance and/or earlier onset of fatigue, as well as impaired glycogen resynthesis. Given the degree of loading of the lower body musculature and connective tissue associated with running, it may be advisable to engage in light exercise that does not load the muscles in the same fashion as running while recovering from DOMS.	4
Clarkson et al. [28]	1986	Randomized Controlled Study	N=28 college age females	CK Levels Perceived Soreness	The magnitude of the post-exercise increase in perceived soreness was greatest for the eccentric and the isometric exercises with minimal soreness following the concentric exercise.	4

					Due to multiple factors which can affect serum CK levels, the increase in serum CK activity may not provide a sensitive indicator of the magnitude of the injury.	
Chattong et al. [8]	2010	Cohort Study	N=20 resistance trained males	VJ Height Knee Height Standing Reach	Used weighted vest equivalents of 5, 10, 15 and 20% of participant's body weight. Resting times between VJ ranged from 10-15 seconds as previous studies have observed no significant decrease in jumping performance with resting periods of similar length.	7
Jakeman et al.[29]	2012	Cohort Study	N=17 females	Plasma CK Levels Maximum Torque Optimum Angle Muscle Soreness	Participants completed 10 × 10 plyometric drop jumps from a 0.6 meter box to induce muscle damage. Plyometric exercise had a significant effect ($p \leq 0.05$) on all indices of muscle damage (muscle soreness, CK levels, knee extensor concentric strength, and VJ performance).	5
Brazen et al.[5]	2010	Quasi-Experimental	N=24 healthy participants (12 females & 12 males)	Knee Flexion Ankle Plantar Flexion Peak VGRF	Had participants do single-leg drop landings from 0.36 meter box. Participants landed with more knee flexion and ankle plantar flexion, had greater peak VGRFs, and required longer times to stabilize the body after landing. The increased times to stability after fatigue suggest delayed reaction times to potentially injurious forces, which may increase injury risk during activity.	6
Sorichter et al. [30]	2001	Quasi-Experimental	N=18	Plasma CK Levels	Participants performed 20 minutes of	5

			(9 females & 8 males)	Lactate sTnI blood levels	downhill treadmill running with 16% decline with a target heart rate of 70% of the individual VO_2 peak. sTnI is a protein unique to skeletal muscle, and elevated plasma levels indicates derangement of the myofibrillar apparatus.	
Vaile et al.[31]	2008	Randomized Crossover Design	N=38 strength trained males	Isometric Squat Force Squat Jump Performance Blood markers (CK, Mb, IL-6, LDH) Perceived Soreness	DOMS-inducing exercise protocol consisted of 5x10 eccentric bi-lateral leg press contractions with a load of 120% of one repetition maximum followed by 2x10 at a load of 100% of one repetition maximum.	4

Table 4: Review of research on strength training in regards to injury & injury prevention

Author(s)	Year	Study Design	n	Outcome Variables	Main Outcomes	PEDro Scale
Faigenbaum et al. [32]	2010	Systematic Review	Subjects ages from 6-16 (males & females)	Youth Resistance Training Injuries Strength Training to Prevent Injuries	This paper suggests that most injuries related to youth resistance training are a result of inadequate professional supervision, which underlies poor exercise techniques and inappropriate training loads. Comprehensive conditioning program designed and supervised by qualified professionals appear to be an effective strategy for reducing sports-related injuries in young athletes.	N/A
Stearns et al. [33]	2013	Quasi-Experimental	40 recreationally active athletes (20 males & 20 females)	Maximum Isometric Strength (knee extensors & hip flexors) Knee & Hip Extensor Moments Peak knee & Hip Flexion Angle Average Knee Adductor Moment	Women demonstrated a kinetic and kinematic profile during landing that is suggestive of increased risk for ACL injury. Women exhibited decreased isometric strength of both knee and hip extensors when compared with men.	6
Machin et al. [34]	2013	Quasi-Experimental	48 recreationally active males	Isometric Knee Extensor Strength Maximum Cycling Power VJ Height Sprint Time	There were significant relationships between isometric knee extensor strength and both maximal cycling power and VJ height. It was concluded that Maximal cycling power is a reliable method to assess decrements in neuromuscular power and athletic	4

					performance after a bout of muscle damaging eccentric exercise.	
Halson [35]	2014	Review Article	N/A	Power Output, Speed, and Acceleration Time-Motion Analysis Neuromuscular Function RPE Heart Rate	Ensuring that fatigue is titrated appropriately is important for both adaptations to training as well as for competition performance. Load monitoring is implemented to try to reduce the risk of injury, illness, and nonfunctional overreaching.	N/A
Herman et al.[36]	2008	Controlled Laboratory Study	66 recreationally active females	Knee Varus/Valgus Peak VGRF Tibial Anterior Shear Force	Strength training alone does not alter knee and hip kinematics and kinetics in female recreational athletes. Strength training as a single intervention method may not be sufficient to reduce the risk of noncontact ACL injuries in female recreational athletes.	8
Chappell et al.[37]	2008	Controlled Laboratory Study	N=30 NCAA D1 female soccer and basketball athletes	Knee Flexion Knee Valgus Moment VJ Height	Completion of a 6-week neuromuscular training program improved select athletic performance measures and changed movement patterns during jumping tasks in the subject population. The use of this neuromuscular training program could potentially modify the collegiate athlete’s motion strategies, improve	5

					performance, and lower the athlete's risk for injury.	
Knapik et al. [38]	1991	Longitudinal Study	N=138 female college athletes	Knee Flexors & Extensors Hip Flexors & Extensors Extensor/Flexor Ratios	There was a trend for higher injury rates to be associated with knee flexor or hip extensor imbalances of 15% or more on either side of the body. The data demonstrates that specific strength and flexibility imbalances are associated with LE injuries in female collegiate athletes.	6
Hewett et al.[39]	1999	Quasi-Experimental	1263 athletes (males & females)	Injury Incidence Female Trained Group Untrained Female Group Male Untrained Group	There were 14 serious knee injuries in the 1263 athletes tracked throughout the study. This prospective study demonstrated a decreased incidence of knee injury in female athletes after a specific plyometric training program.	4
Mair et al. [40]	1995	Quasi-Experimental	N=22 male subjects	Plasma CK Levels VJ Height MHC cTnI	The initial exercise resulted in an increase in CK and MHC, a decrement in muscle force, and DOMS in all participants.	5

Summary

Strength and conditioning training for athletes is rapidly growing worldwide. Strength training is a key component to helping athletes improve strength, power and endurance, all while helping minimize injury risk.[32,34,37] However, even the best training programs will lead to the athlete experiencing some form of DOMS. Previous research has shown that DOMS can lead to prolonged muscle force loss, reduction of joint range of motion, lower shock attenuation, reduced peak torque, and a sensation of unsteady limbs and clumsiness in precision movements. If athletes participate in activities of high-impact, this may cause harm to the athlete by increasing the forces placed onto the lower extremities resulting in a greater risk of injuries.[38,39] Recent research has begun to look into the effects DOMS has on various lower extremity movements such as walking, running, and single-leg landings. To our knowledge, no research has been done looking at the effects it has on athlete's jumping mechanics and performance.

In order for strength professionals to decrease injury risk while increasing athletic performance, athletes need to be involved in strength training programs. However, further research needs to be completed to fully understand the implications DOMS has on jumping mechanics and performance. Understanding these effects will help aid coaches, clinicians, athletic trainers, and strength and conditioning professionals in providing proper care, treatment, and workouts that will minimize potential injuries related to DOMS. Improving sports performance and movement

mechanics while reducing injury risk will help improve the longevity of athletes competing in their sport.

ABSTRACT

THE EFFECT OF DELAYED ONSET MUSCLE SORENESS ON JUMPING MECHANICS AND PERFORMANCE

RYAN J. ENGELS

2017

Background: Delayed onset muscle soreness (DOMS) is an exercise-induced muscle soreness resulting from high-intensity eccentric muscular contractions. DOMS appears to be more prevalent in athletes at the beginning of an athletic season or when new movements or exercise are first introduced. The acute effect of DOMS on jumping mechanics is currently unknown. **PURPOSE**: The purpose of this study is to determine the effect of delayed onset muscle soreness on vertical jump performance and jumping mechanics. **METHODS**: Twenty college aged, recreationally active males participated in this study (age: 21.54 ± 2.61; height: 1.82 ± 0.067; mass: 81.36 ± 9.53). Participants were randomly assigned to the experimental (EXP) and control (CON) groups. Ground reaction forces (1000Hz) and motion capture (200Hz) were recorded for each of the 5 submaximal jump trials both PRE and POST Intervention. The intervention included two 15 minute runs with a 5 minute rest between. Participants in the CON group ran at a 0% grade while the EXP ran at a 10% decline. Participants then completed 4x10 of weighted box drop landing (EXP) or weighted box jumps (CON) with weight equal to 20% of their total body weight. Variables of interest during the landing portion of the jump can be found in the table below. A one-way ANOVA was conducted to compare percent change (POST-PRE) for each variable were compared across groups. **RESULTS**: Results of the study show that the EXP group experienced significantly greater soreness following their exercise protocol. All other variables of interest saw no statistically significant changes between PRE and POST exercise protocols. **CONCLUSION**: Data from this study suggests that the EXP group experienced significantly greater soreness following their exercise protocol. However, no changes to the landing mechanics during the vertical jump appear to be associated with the increased muscle soreness.

Introduction

Delayed onset muscle soreness (DOMS) is an exercise-induced muscle soreness resulting from high-intensity eccentric muscular contractions.[1] DOMS appears to be more prevalent in athletes at the beginning of an athletic season or when new movements or exercise are first introduced, and is common for both the elite and novice athlete.[2] The pain and stiffness associated with DOMS is typically felt in muscles approximately 24 to 72 hours after the exercise. Behrens et al.[3] explains that DOMS is caused by eccentric (lengthening) exercise, which causes micro-trauma to the muscle fibers. It has been suggested that with the increase in muscle soreness and pain there is a natural decrease in performance. Recent research has started to investigate the effect DOMS has on the body during performance. Vila-Chã et al.[4], reports that DOMS is associated with prolonged muscle force loss, reduction of joint range of motion, lower shock attenuation, reduced peak torque, and a sensation of unsteady limbs and clumsiness in precision movements.

In addition to a reduction in sports performance caused by DOMS, recent studies suggest that changes also occur in the athlete’s movement mechanics. Researchers have investigated the effect DOMS has on lower extremity biomechanics of various movements such as walking, running, and single-leg drop landings.[5, 6] Chappell et al.[7] reported that athletes with DOMS have an increased peak proximal tibial anterior shear force, decreased knee flexion angle, and increased ground contact forces during a series of stop-jumps tasks. This added stress, on top of poor landing mechanics, is likely to increase injury risk to athletes while diminishing performance. To our best understanding, no studies have looked at the effects DOMS has on jumping mechanics and performance during sports/training related activities. Previous studies have looked specifically at the effects DOMS has on certain movements, but has not compared the findings with a control group.

Understanding the effect of DOMS on performance and movement mechanics will aid coaches, clinicians, athletic trainers, and strength and conditioning professionals in providing proper care, treatment, and workouts that will minimize potential injuries related to DOMS. In particular it will help coaches avoid overtraining and introducing new exercises and movements in the days leading up to competition. Improving sports performance and movement mechanics and reducing injury risk will help improve the longevity of athletes competing in their sport.

The purpose of this study is to determine the effect of delayed onset muscle soreness on vertical jump performance and jumping mechanics. The two objectives of this study are to determine the effect of DOMS on vertical jump height by comparing pre-post changes, and determine the effect of DOMS on jumping mechanics by comparing pre-post changes between a control group and an experimental group. We hypothesize that the experimental group will display lower vertical jump heights and muscular power following the DOMS-inducing protocol compared to the control group. We also hypothesize that the experimental group will display greater changes in joint angles, joint reaction forces, and joint powers during the vertical jump compared to the control group. The changes we expect to see are decreased joint motion and increased vertical loading in the experimental group.

Methods

Participants

Twenty college aged, recreationally active males were randomly assigned to a control (Age: 20.4 ± 1.71, Height: 1.83 ± 0.061 m, and Mass: 82.68 ± 6.78 kg) or experimental group (Age: 22.8 ± 3.12, Height: 1.81 ± 0.079 m, and Mass: 78.67 ± 12.05 kg). We defined recreational athlete as exercising a minimum of three 60 minutes sessions per week. As part of their exercise program participants must include at least 60 minutes or 9 miles of running per week. Participants were recruited by word of mouth and by visiting various university clubs and activities. For at least three months leading up to the study, all participants were healthy, free of illness/injury or any other medical condition inhibiting their ability to safely run/jump in a laboratory setting.

Experimental Protocol

Participants completed three 60-90 minute testing sessions with 48 hours between each testing session. During the first session of the study, informed consent was obtained and the Physical Activity Readiness Questionnaire was completed. Participants then completed a health history questionnaire and age, height, and weight were measured and recorded. Participants then completed a VO2 max test to determine the treadmill running speed. Participants started with a two minute warm-up at self-selected speed. To start the VO2 max test the speed of the treadmill was set to six mph at a 1% grade. At the two and four minute mark, the speed was increased to seven and eight mph, respectively. Starting at six minutes, the speed remained constant and the grade of the treadmill was increased 1% every two minutes until volitional fatigue. The results from this test were used to determine running speeds for the treadmill protocol by finding the speed where 70% of maximum VO2 was reached and maintained.

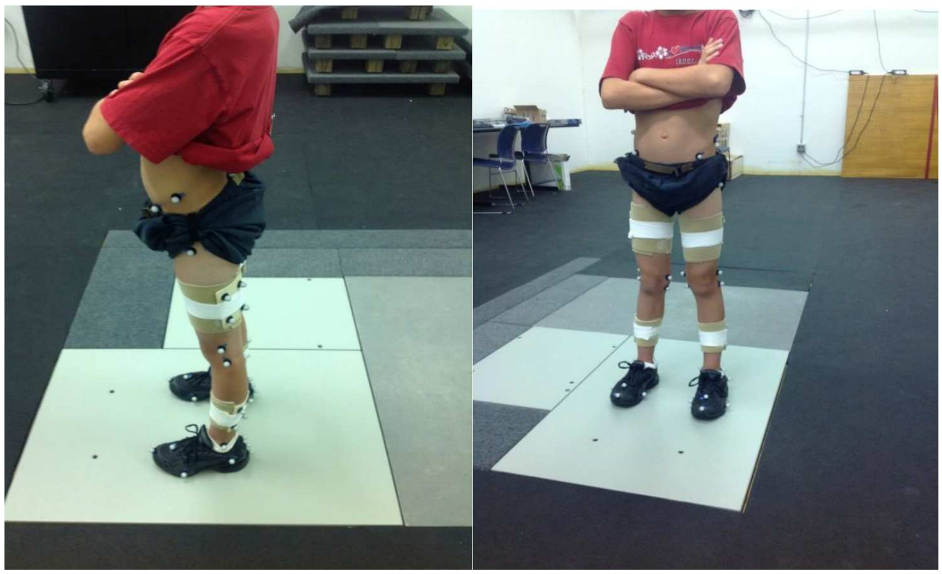

Figure 1: Example of reflective marker placement

The second session started with participants rating their level of muscle soreness using a step-down test. Using a Visual Analog Scale (0= no soreness-10=severe soreness), participants were asked to rate the feeling of pain/soreness as they descended a flight of ten stairs. Participants were then fitted for standardized Nike Pegasus footwear and completed a five minute dynamic warm-up that included jogging, side shuffle, carioca, walking lunges with a twist, backwards lunges with a reach overhead, high knees, butt kicks, monster crawls with a twist, single leg RDL, toy soldiers, jumping jacks, and squat jumps. The participants then performed a max vertical jump test using the Vertec Jump tester following the standard protocol for evaluating max vertical jump height.[8] Following max vertical jump testing, reflective markers were placed on the anterior, posterior, and lateral portions of the shoe, lateral and medial malleolus, lateral and medial condyles of the knee, greater trochanter, ASIS, superior border of the iliac crest (IC), and lumbosacral section of the spine (Figure 1). Marker clusters were then attached to thighs, shanks, and the sacrum to aid in three-dimensional tracking. Participants then completed five to ten submaximal vertical jump trials with a predetermined reach point (75% of max vertical jump height). Ground reaction forces (1000Hz) and kinematic data (200Hz) were recorded for each of the jump trials. For the jumping trials, participants were instructed to start with one foot on each AMTI force platform and jump vertically reaching with both hands as to the set reach point, and landing with one foot on each force plate (Figure 2). Trials were excluded if the participant: a) did not strike each force plate separately with each foot, b) did not reach the reach point or jumped more than 2 inches higher than the reach point, and/or c) was unable to maintain balance upon landing. Participants were then randomly assigned to the experimental or control groups.

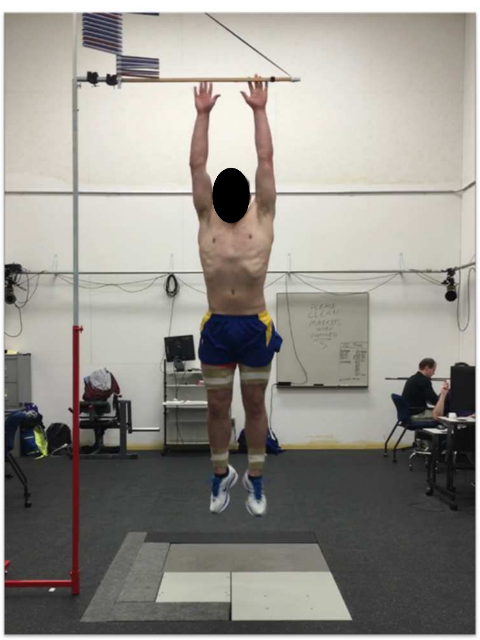

Figure 2: Participant completing submax jump trials

Intervention

Following the biomechanical analysis of the second session, participants were randomly placed into either the level treadmill running protocol (Control Group) or the downhill treadmill running protocol (Experimental Group).

Both groups completed two 15 minute runs with a five minute rest between. Participants in the level treadmill running protocol ran at a 0% grade at the speed where 70% of their maximum VO2 occurred and was maintained during the VO2 max test of session one. Participants in the downhill treadmill running protocol ran at a 10% decline at the speed where 70% of maximum VO2 occurred and was maintained during the VO2 max test of session one. Following the running protocol participants completed 4 sets of 10 reps of weighted box jumps (Control Group) or weighted box drop landings (Experimental Group) at a set height of 24 inches. Participants in the control group completed weighted box jumps to focus on the concentric muscle action of the movement, while the participants in the experimental group completed weighted box drop landings which focused on the eccentric muscle action of the movement. The weight used for each participant was equivalent to 20% of their total body weight. Session three occurred 48 hours after session two and repeated the same procedures in session two with the exception that they did not complete the treadmill running protocol or the weighted box jumps.

Data Analysis

Reflective markers were labeled then digitized using Qualisys Track Manager Software (Qualisys, Gothenburg, Sweden). The digitized markers were used to calculate joint motion using Visual 3-D (C-Motion, Inc., Germantown, MD). Marker data was filtered with a recursive 4th order Lowpass Butterworth filter with a cutoff frequency of 6 Hz. Three-dimensional joint and segment angles were calculated with Visual 3-D software (C-Motion, Inc., Germantown, MD) using an X, Y, Z Euler angle rotation sequence. Kinematic variables of interest included sagittal plane excursions of the hip, knee, and ankle joints during both the takeoff and landing of the vertical jump trials. Customized software (LabVIEW 8.0; National Instruments, Austin, TX) was used to extract the variables of interest from the motion files. The average of five trials was used for the statistical comparisons.

Ground reaction force data was filtered with a recursive 4th order Butterworth filter with a cutoff frequency of 50 Hz. Force data was normalized to body weight for group comparisons with the average of five trials for each task being used for statistical comparison. Kinetic variables of interest from the ground reaction force data during the submaximal jumps included the average and max rate of force development during the jumping phase, jump impulse, max vertical ground reaction force upon landing, and the vertical instantaneous load road during landing.

Joint kinematics combined with the segment inertial properties were used to determine internal joint moments at the ankle, knee, and hip. The maximum moment for the hip, knee and ankle joints in the sagittal plane were calculated, and averaged over five trials for each participant. Joint moments and powers were normalized to body weight and height.

Statistical Analysis

A repeated measures (PRE vs POST) mixed model (CON vs EXP) ANOVA was used to determine the time x group interaction of each variable of interest using SPSS software (Version 22.0, IBM® SPSS® Statistics, Chicago, IL, USA). Effect size was calculated utilizing Cohen's d with 0.2, 0.5 and 0.8 considered small, medium and large respectively. The level of significance was set at $p < 0.05$. Data were presented as means and standard deviations.

Results

Muscle Soreness

Results from the muscle soreness differences for the CON and EXP group are seen below in Table 1. For muscle soreness the experimental group (EXP) experienced significantly greater soreness following their exercise protocol (p=0.001).

Vertical Jump Height and Ground Reaction Forces

Results of the ground reaction force variables during the jumping and landing phases, as well as max vertical jump changes are found in Table 1. No ground reaction force variables reached significance. While only two approached statistical significance, they were the non-dominant (ND) jump impulse (p= 0.07), and the ND average rate of force development (RFD) (p=0.07). No differences in maximum vertical jump height or maximum vertical ground reaction forces during landing were detected.

Table 1: Mean ± SD of the difference scores (POST-PRE) and *p*-values of the Time and Time x Group Interactions for the Ground Reaction Forces.

Variable	CON	EXP	Time *p*-value	Time x Group *p*-value	*d*
Soreness (Δ Visual Analogue Scale)	0.50 ± .71	3.11 ± 1.90	.000*	.001*	1.82
Max Vert. Jump (Δ inches)	0.25 ± 1.11	-0.50 ± 0.90	0.60	0.13	0.74
ND Max Fz Jump (ΔBW)	-.001 ± 0.10	0.01 ± 0.04	0.76	0.73	0.14
D Max Fz Jump (ΔBW)	0.01 ± 0.10	0.02 ± 0.05	0.43	0.80	0.13
ND Jump Imp. (ΔBW)	-0.04 ± 0.07	0.02 ± 0.05	0.45	0.07	0.99
D Jump Imp. (ΔBW)	-0.003 ± 0.06	0.01 ± 0.04	0.78	0.61	0.25
ND max RFD Jump (ΔBW)	0.13 ± 1.55	-0.47 ± 1.11	0.59	0.34	0.45
D max RFD Jump (ΔBW)	-0.30 ± 1.20	-0.52 ± 1.80	0.25	0.75	0.14
ND ave RFD Jump (ΔBW)	0.33 ± 0.76	-0.21 ± 0.39	0.66	0.07	0.89
D ave RFD Jump (ΔBW)	0.27 ± 0.93	-0.09 ± 0.26	0.58	0.28	0.53
ND max vGRF Land (ΔBW)	0.02 ± 0.37	0.19 ± 0.20	0.16	0.25	0.57
D max vGRF Land (ΔBW)	0.14 ± 0.47	0.15 ± 0.39	0.17	0.94	0.02
ND VILR Land (ΔBW/s)	-6.19 ± 30.99	2.89 ± 11.22	0.77	0.42	0.39
D VILR Land (ΔBW/s)	2.39 ± 26.14	8.21 ±22.24	0.36	0.61	0.24

EXP=Experimental Group; CON=Control Group; BW=Body Weights; *= Statistically Significant

Joint Kinematics

Results of the ankle, knee, and hip angle changes that occurred during the jumping and landing phases are found in Table 2. ND max hip flexion during the jumping phase showed statistical significance (*p*=0.03) in regards to time. This indicates to us that both groups significantly decreased hip flexion excursion. The only other variable that approached statistical significance was the D max hip flexion during the jumping phase. No other differences were found in the other variables of interest.

Table 2: Mean ± SD of the difference scores (POST-PRE) and *p*-values of the Time and Time*Group Interactions for the Joint Excursions

Variable	CON	EXP	Time *p*-value	Time*Group *p*-value	*d*
ND max Dorsiflex Jump (Δ degrees)	0.21 ± 4.27	-0.10 ± 4.57	0.96	0.88	0.07
D max Dorsiflex Jump (Δ degrees)	-1.67 ± 2.45	-0.21 ± 3.49	0.19	0.30	0.48
ND max Knee Flex Jump (Δ degrees)	1.58 ± 7.33	2.48 ± 10.01	0.33	0.83	0.10
D max Knee Flex Jump (Δ degrees)	3.44 ± 8.43	0.45 ± 10.16	0.38	0.49	0.32
ND max Hip Flex Jump (Δ degrees)	-5.29 ± 11.83	-8.42 ± 13.57	0.03*	0.60	0.25
D max Hip Flex Jump (Δ degrees)	-5.27 ± 12.25	-6.43 ± 14.30	0.07	0.85	0.09
ND max Platar Flex Land (Δ degrees)	-0.14 ± 4.52	0.44 ± 3.53	0.87	0.76	0.14
D max Platar Flex Land (Δ degrees)	-0.48 ± 4.16	0.15 ± 3.13	0.85	0.72	0.17
ND Ankle Angle at Contact (Δ degrees)	0.52 ± 4.00	-0.11 ± 4.00	0.83	0.74	0.16
D Ankle Angle at Contact (Δ degrees)	0.35 ± 3.92	0.74 ± 2.71	0.50	0.80	0.12
ND max Knee Flex Land (Δ degrees)	-0.34 ± 8.39	5.34 ± 7.39	0.19	0.14	0.72
D max Knee Flex Land (Δ degrees)	1.23 ± 7.80	3.17 ± 7.63	0.23	0.59	0.25
ND Knee Angle at Contact (Δ degrees)	0.77 ± 4.09	1.56 ± 3.27	0.19	0.65	0.21
D Knee Angle at Contact (Δ degrees)	2.25 ± 3.36	-0.39 ± 4.87	0.34	0.18	0.63
ND max Hip Flex Land (Δ degrees)	0.14 ± 16.28	-6.68 ± 11.24	0.33	0.31	0.49
D max Hip Flex Land (Δ degrees)	-0.20 ± 15.77	-4.34 ± 12.52	0.50	0.54	0.29
ND Hip Angle at Contact (Δ degrees)	2.11 ± 8.14	-0.17 ± 5.66	0.56	0.49	0.33
D Hip Angle at Contact (Δ degrees)	0.88 ± 7.80	1.76 ± 7.58	0.46	0.81	0.11
ND Dorsi excursion Land (Δ degrees)	-0.66 ± 3.73	0.56 ± 3.50	0.95	0.48	0.34
D Dorsi excursion Land (Δ degrees)	-0.83 ± 2.89	-0.59 ± 4.02	0.38	0.89	0.07
ND Knee Flex excursion Land (Δ degrees)	-1.11 ± 6.24	3.77 ± 5.57	0.34	0.09	0.83
D Knee Flex excursion Land (Δ degrees)	-1.02 ± 6.51	3.55 ± 4.60	0.35	0.10	0.81
ND Hip Flex excursion Land (Δ degrees)	-1.97 ± 17.45	-6.51 ± 9.05	0.21	0.49	0.33
D Hip Flex excursion Land (Δ degrees)	-1.08 ± 18.38	-6.11 ± 9.75	0.31	0.47	0.34

EXP=Experimental Group; CON=Control Group; BW=Body Weights; *= Statistically Significant

Joint Kinetics

Results of the ankle, knee and hip moments and powers from the jumping and landing phases are shown in Table 3. Only one variable of interest in the joint kinetics experienced statistical significance for time x group interaction and that was D knee moment max land (*p*=0.03). No other significant differences for the time x group interaction were found for joint kinetics. However, COM vertical displacement had a main effect for time. This indicates to us that both groups significantly changed.

Table 3: Mean ± SD of the difference scores (POST-PRE) and *p*-values of the Time and Time*Group Interactions for the Joint Moments and Powers

Variable	**CON**	**EXP**	**Time *p*-value**	**Time x Group *p*-value**	***d***
ND Ankle Dorsiflex Moment Jump (Δ degrees)	-0.03 ± 0.14	-0.03 ± 0.08	0.31	0.92	0.00
D Ankle Dorsiflex Moment Jump (Δ degrees)	0.03 ± 0.09	-0.02 ± 0.07	0.86	0.19	0.62
ND Knee Flexor Moment Jump (Δ degrees)	-0.01 ± 0.19	-0.01 ± 0.12	0.77	0.99	0.00
D Knee Flexor Moment Jump (Δ degrees)	-0.05 ± 0.12	-0.01 ± 0.12	0.27	0.53	0.33
ND Hip Flexor Moment Jump (Δ degrees)	0.05 ± 0.40	0.07 ± 0.17	0.41	0.92	0.07
D Hip Flexor Moment Jump (Δ degrees)	0.11 ± 0.40	0.02 ± 0.08	0.36	0.50	0.31
ND Ankle Plantar Flex Power Jump (Δ degrees)	4.79 ± 124.18	30.22 ± 69.97	0.47	0.60	0.25
D Ankle Plantar Flex Power Jump (Δ degrees)	-12.68 ± 40.80	-4.50 ± 38.84	0.36	0.66	0.21
ND Knee Extensor Power Jump (Δ degrees)	-7.98 ± 82.97	0.15 ± 73.31	0.83	0.83	0.10
D Knee Extensor Power Jump (Δ degrees)	-19.92 ± 52.76	21.27 ± 44.99	0.95	0.09	0.84
ND Hip Extensor Power Jump (Δ degrees)	3.74 ± 67.37	-10.46 ± 47.34	0.81	0.61	0.24
D Hip Extensor Power Jump (Δ degrees)	-18.64 ± 69.00	-3.50 ± 25.63	0.38	0.54	0.29
COM Vert displacement	-0.01 ± 0.02	-0.02 ± 0.02	0.03*	0.35	0.50
ND Ankle Plantar Flex Moment Land (Δ degrees)	-0.005 ± 0.16	0.06 ± 0.10	0.39	0.32	0.49
D Ankle Plantar Flex Moment Land (Δ degrees)	0.08 ± 0.06	0.01 ± 0.16	0.11	0.23	0.58
ND Knee Flex Moment Land (Δ degrees)	-0.12 ± 0.31	-0.01 ± 0.19	0.30	0.38	0.43
D Knee Flex Moment Land (Δ degrees)	-0.14 ± 0.17	0.04 ± 0.17	0.23	0.03*	1.46
ND Hip Flex Moment Land (Δ degrees)	-0.10 ± 0.34	0.05 ± 0.37	0.71	0.36	0.42
D Hip Flex Moment Land (Δ degrees)	0.11 ± 0.30	-0.02 ± 0.33	0.53	0.39	0.41

EXP=Experimental Group; CON=Control Group; BW=Body Weights; *=Statistically Significant

Discussion

The two objectives of the study were to; 1. determine the effect of DOMS on vertical jump height by comparing pre-post changes between an experimental and control group, and 2. determine the effect of DOMS on jumping mechanics by comparing pre-post changes between the experimental and control group. We hypothesized that the EXP group would display greater changes in muscle soreness, lower vertical jump heights, and greater changes to vertical jumping and landing mechanics. The results of this study indicated that the EXP group did experience significantly greater soreness following their exercise protocol. However, no significant changes were found in the vertical jump performance and few changes were found in the vertical jumping movement mechanics.

Muscle Soreness

Our results indicate that 30 minutes of downhill running followed by 4 sets of 10 reps of weighted box drop landings provided sufficient eccentric loading of the quadriceps muscles to elicit DOMS. It is interesting to note that of the 10 participants in the EXP group, seven indicated an increase of pain of 2-6.5 points. In comparison, among the control participants only one participant indicated an increase of soreness of 2 points, 3 participants an increase of one point, and the remaining 6 participants indicated no increase in muscle soreness 48 hours after 30 minutes of level running and 4 sets of 10 weighted box jumps. Even though the overall exercise load was equivalent across groups, the exercises involving eccentric loading resulted in greater muscle soreness. Our results are consistent with other studies reporting that when participants take part in an unfamiliar eccentric based activity they experience greater levels of soreness than when they complete concentric based movements.[3,9,12]

Vertical Jump Height and Ground Reaction Forces

It has been suggested that DOMS leads to a reduction in force output profiles.[2,4] In the present study however, the findings did not support the contention that DOMS leads to a reduction in vertical ground reaction force profiles during the vertical jump and landing. As seen in Table 1, there were no significant changes to peak vertical ground reaction forces, vertical impulses, rates of force development or vertical loading rates. There were also no changes in the vertical jump heights, which is to be expected with no change in force output profiles. One possible reason other studies may have found changes could be due to the lack of a control group in their studies. If a participant experiences a clinical improvement during a study, a well-designed study with an appropriate control group will enable the improvements to be attributed to the intervention itself, thus strengthening the validity and credibility of the findings.[41] As such, the design of a control group is as critical as the design of the intervention group. Thus, the other studies may have seen differences that had they had a control group to compare to would not see.

Joint Kinematics & Kinetics

The results from the joint kinematic and kinetic data showed that only the max knee flexor moment of the dominant leg during the landing phase was significantly different. Otherwise, there were no significant changes in any of the variables of interest, with only landing phase D and ND knee flex excursion and jump phase D Knee Power max approaching significance. This differs from the findings of previous studies, which showed that when people are experiencing muscle soreness they altered jumping and landing mechanics.[2,17,18] These results also suggest that altered jumping mechanics can lead to an increased risk of LE injury.[4,19] In the present study, findings did not support the hypothesis that increased muscle soreness resulting from DOMS leads to changes in kinetic and kinematic data that could potentially lead to higher injury risk. By looking at Table 2 and Table 3 we can see that nearly all variables of interest showed no significant difference. One possible explanation for this can be that the participants had different jumping mechanics. Each individual's mechanics varied which lead to differing results and caused the high standard deviations between groups. This as well as the sample size may have been too small to detect statistical significance considering the high levels of variability. Another possible explanation why the results varied greatly is due to the lack of control for outside variables. Participants in the CON group could have been participating in activities that made them sorer, while the EXP group could have been participating in activities that helped alleviate their soreness. To control these outside variables we handed out sheets and told participants what they were supposed to do. The last possible explanation why we did not see the results we expected to see could be because of a warmup effect. A proper warm up prior to exercise could work to alleviate the possible effects of DOMS on vertical jump performance and mechanics. In our warmup we had our participants complete a dynamic warm-up that included jogging, side shuffle, carioca, walking lunges with a twist, backwards lunges with a reach overhead, high knees, butt kicks, monster crawls with a twist, single leg RDL, toy soldiers, jumping jacks, and squat jumps. This warmup could have been enough to help alleviate some of DOMS effects. Findings have shown that moderate aerobic warm-up or cool-down exercise, with mainly concentric muscle work, can be recommended to attenuate muscle soreness following intensive leg resistance exercise.[42]

Conclusion

The results of the study indicate that the EXP group experienced significantly greater soreness following their exercise protocol. However, no changes to vertical jump performance, and minimal changes to the jumping and the landing mechanics were associated with the increased muscle soreness. Therefore, we suggest that the lack of findings in kinetic and kinematic data may be related to normal landing mechanic variations between participants, lack of activity control outside the study, and a relatively small sample size. Further study recommendations include controlling for outside activity and increasing the sample size to verify the findings of DOMS on vertical jump performance and mechanics. Also, further studies should investigate to see if proper warmups help minimize the effects DOMS may generate on vertical jump performance and mechanics. Future research needs to be done to determine if the findings of this study may indicate that there is a minimal effect, and that other studies were limited because they had no control group.

Limitations

A Study limitation was the lack of participant activity control outside of the study. Since an athlete's activity levels or lack thereof following a workout, can greatly influence how their bodies adapt and recover to the stresses of delayed onset muscle soreness. A second limitation of the study was a familiarity response. Since the study called for recreational athletes, not all participants were familiar with vertical jump testing. This means that although the participants may have been significantly sorer, they may have felt more comfortable and able to perform the tasks they had to complete on the second and third session better. A third limitation could be that participants in the EXP group did not receive enough soreness to elicit a response. Of the ten participants only two indicated an increase in pain of 3+ points. A fourth limitation was that the participants of this study had vastly different jumping/landing mechanics which lead to a wide variance. Lastly, the sample size may have been too small for the type of results we wanted to see.

References

1. Armstrong RB. Mechanisms of exercise-induced delayed onset muscular soreness: a brief review. *Med Sci Sports Exerc.* 1984; 16 (6):529-538.
2. Cheung K, Hume P, Maxwell L. Delayed onset muscle soreness: treatment strategies and performance factors. *Am J Sports Med.* (Auckland, N.Z.). 2003; 33 (2):145-164.
3. Behrens M, Mau-Moeller A, Bruhn S. Effect of exercise-induced muscle damage on neuromuscular function of the quadriceps muscle. *Int J Sports Med*. 2012; 33 (8):600.
4. Vila-Chã C, Hassanlouei H, Farina D, Falla D. Eccentric exercise and delayed onset muscle soreness of the quadriceps induce adjustments in agonist–antagonist activity, which are dependent on the motor task. *Exp. Brain Res*. 2012; 216 (3):385-395.
5. Brazen DM, Todd MK, Ambegaonkar JP, Wunderlich R, Peterson C. The Effect of Fatigue on Landing Biomechanics in Single-Leg Drop Landings. *Clin J Sports Med*. 2010; 20 (4):286-292.
6. Braun WA, Dutto DJ. The effects of a single bout of downhill running and ensuing delayed onset of muscle soreness on running economy performed 48 h later. *Eur J Appl Physiol*. 2003; 90 (1-2):29-34.
7. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A Comparison of Knee Kinetics between Male and Female Recreational Athletes in Stop-Jump Tasks. *Am J Sports Med*. 2002; 30 (2):261-267.
8. Chattong C, Brown LE, Coburn JW, Noffal GJ. Effect of a dynamic loaded warm-up on vertical jump performance. *J Strength Cond Res*. 2010; 24 (7):1751-1754.
9. Kanda K, Sugama K, Hayashida H, et al. Eccentric exercise-induced delayed-onset muscle soreness and changes in markers of muscle damage and inflammation. *Exerc Immunol Rev*. 2013; 19:72-85.
10. Kauranen K, Siira P, Vanharanta H. Delayed-onset muscle soreness and motor performance of the upper extremity. *Eur J Appl Physiol*. 2001; 84 (4):302-309.
11. Hedayatpour N, Falla D, Arendt-Nielsen L, Farina D. Effect of delayed-onset muscle soreness on muscle recovery after a fatiguing isometric contraction. *Scand J Med Sci Sports*. 2010; 20 (1):145-153.
12. Tsatalas T, Giakas G, Spyropoulos G, et al. The effects of eccentric exercise-induced muscle damage on running kinematics at different speeds. *J Sports Sci*. 2013; 31 (3):288-298.
13. Chen TC, Lin K-Y, Chen H-L, Lin M-J, Nosaka K. Comparison in eccentric exercise-induced muscle damage among four limb muscles. *Eur J Appl Physiol*. 2011; 111 (2):211-223.
14. Cleak MJ, Eston RG. Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *Br J Sports Med*. 1992;26(4):267-272.
15. Clarkson PM, Nosaka K, Braun B. Muscle function after exercise-induced muscle damage and rapid adaptation. *Med Sci Sports Exerc*. 1992; 24 (5):512-520.
16. Schmitz RJ, Cone JC, Copple TJ, Henson RA, Shultz SJ. Lower-extremity biomechanics and maintenance of vertical-jump height during prolonged intermittent exercise. *J Sport Rehabil*. 2014; 23 (4):319-329.

17. Willson JD, Binder-Macleod S, Davis IS. Lower extremity jumping mechanics of female athletes with and without patellofemoral pain before and after exertion. *Am J Sports Med*. 2008; 36 (8):1587-1596.
18. Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. Comparison of Landing Biomechanics Between Male and Female Dancers and Athletes, Part 2: Influence of Fatigue and Implications for Anterior Cruciate Ligament Injury. *Am J Sports Med*. 2014; 42 (5):1089-1095.
19. Kernozek TW, Torry MR, Iwasaki M. Gender Differences in Lower Extremity Landing Mechanics Caused by Neuromuscular Fatigue. *Am J Sports Med*. 2008; 36 (3):554-565.
20. Wesley CA, Aronson PA, Docherty CL. Lower Extremity Landing Biomechanics in Both Sexes After a Functional Exercise Protocol. *J Athl Train*. 2015; 50 (9):914-920.
21. Ortiz A, Olson SL, Etnyre B, Trudelle-Jackson EE, Bartlett W, Venegas-Rios HL. Fatigue effects on knee joint stability during two jump tasks in women. *J Strength Cond Res*. 2010; 24 (4):1019.
22. Byrne PJ, Moran K, Rankin P, Kinsella S. A comparison of methods used to identify 'optimal'drop height for early phase adaptations in depth jump training. *J Strength Cond Res*. 2010; 24 (8):2050-2055.
23. Brazier J, Bishop C, Simons C, Antrobus M, Read PJ, Turner AN. Lower extremity stiffness: Effects on performance and injury and implications for training. *Strength Cond J*. 2014; 36 (5):103-112.
24. Byrnes WC, Clarkson PM, White JS, Hsieh SS, Frykman PN, Maughan RJ. Delayed onset muscle soreness following repeated bouts of downhill running. *J Appl Physiol*. 1985; 59 (3):710-715.
25. Schwane JA, Johnson SR, Vandenakker CB, Armstrong RB. Delayed-onset muscular soreness and plasma CPK and LDH activities after downhill running. *Med Sci Sports Exerc*. 1982;15(1):51-56.
26. Jamurtas AZ, Fatouros IG, Buckenmeyer P, et al. Effects of Plyometric Exercise on Muscle Soreness and Plasma Creatine Kinase Levels and Its Comparison with Eccentric and Concentric Exercise. *J Strength Cond Res*. 2000; 14 (1):68-74.
27. Twist C, Eston R. The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. *Eur J Appl Physiol*. 2005; 94 (5-6):652-658.
28. Clarkson P, Byrnes W, McCormick K, Turcotte L, White J. Muscle soreness and serum creatine kinase activity following isometric, eccentric, and concentric exercise. *Int J Sports Med*. 1986; 7 (03):152-155.
29. Jakeman JR, Eston RG. Joint angle-torque characteristics of the knee extensors following eccentric exercise-induced muscle damage in young, active women. *J Exerc Sci Fit*. 2013; 11 (1):50-56.
30. Sorichter S, Mair J, Koller A, et al. Release of muscle proteins after downhill running in male and female subjects. *Scand J Med Sci Sports*. 2001; 11 (1):28-32.
31. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on the signs and symptoms of delayed onset muscle soreness. *Eur J Appl Physiol*. 2008; 102 (4):447-455.

32. Faigenbaum AD, Myer GD. Resistance training among young athletes: safety, efficacy and injury prevention effects. *Br J Sports Med*. 2010; 44 (1):56-63.
33. Stearns KM, Keim RG, Powers CM. Influence of relative hip and knee extensor muscle strength on landing biomechanics. *Med Sci Sports Exerc*. 2013; 45 (5):935-941.
34. Machin DR, Christmas KM, Van Pelt D, Trombold JR, Coyle EF. Relationships Between Lower Body Muscular Strength and Power After Downhill Running. 2013.
35. Halson SL. Monitoring training load to understand fatigue in athletes. *J Sports Med*. 2014; 44 (2):139-147.
36. Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *Am J Sports Med*. 2008;36(4):733-740.
37. Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med*. 2008; 36 (6):1081-1086.
38. Knapik JJ, Bauman CL, Jones BH, Harris JM, Vaughan L. Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *Am J Sports Med.* 1991; 19 (1):76-81.
39. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes a prospective study. *Am J Sports Med*. 1999; 27 (6):699-706.
40. Mair J, Mayr M, Mullet E, et al. Rapid adaptation to eccentric exercise-induced muscle damage. *Int J Sports Med*. 1995, 16 (06):352-356.
41. Kinser PA, Robins JL. Control Group Design: Enhancing Rigor in Research of Mind-Body Therapies for Depression. *Evidence-based Complementary and Alternative Medicine.*
42. Olsen O, Sjøhaug M, van Beekvelt M, Mork PJ. The Effect of Warm-Up and Cool-Down Exercise on Delayed Onset Muscle Soreness in the Quadriceps Muscle: a Randomized Controlled Trial. *J Hum Kinet*. 2012;35:59-68. doi:10.2478/v10078-012-0079-4.